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Lepton electric dipole moments in supersymmetric type II seesaw model

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Abstract

We study the lepton electric dipole moments in the framework of the supersymmetric type II seesaw model where the exchange of heavy $SU(2)_W$ triplets generates small neutrino masses. We show that the CP violating phase of the bilinear soft supersymmetry breaking term associated with the $SU(2)_W$ triplets contributes to lepton electric dipole moments mainly through threshold corrections to the gaugino masses at the seesaw scale. As a consequence, the ratio of the electric dipole moments of the muon and the electron is the same as the ratio of their masses in a wide region of parameter space.

The electric dipole moments (EDMs) of leptons, nucleons and atoms are important probe for physics beyond the Standard Model. Until now, however, no EDMs has been observed experimentally and only upper limits of them have been obtained [1, 2]. It is known that the upper limits on EDMs strongly constrain CP violating parameters of the new physics sector. In particular, supersymmetric (SUSY) extensions of the Standard Model are the most promising candidates for the physics beyond the Standard Model. The minimal version of them are usually referred to as the Minimal Supersymmetric Standard Model (MSSM). In the framework of the MSSM, new sources of CP violation are introduced in terms of soft SUSY-breaking parameters and are severely constrained by the upper limits on EDMs [3].

Recent neutrino observations tell us the neutrinos have nonzero but tiny masses. The seesaw mechanism [4] is an attractive idea to explain their smallness, in which their masses are generated through the exchange of heavy fields. There are three types of seesaw models depending on the nature of the heavy fields. In the type I model, three generations of gauge singlet fermions (right-handed neutrinos) with large Majorana masses are introduced. The type II model [5] includes heavy $SU(2)_W$ triplet scalar field(s). Heavy $SU(2)_W$ triplet fermions are introduced in the type III model [6].

In the framework of SUSY seesaw models, newly introduced superpotential and soft SUSY breaking terms associated with the heavy fields may contain CP violating phases which contribute to the EDMs of leptons and quarks. Thus the current bounds and future measurements of the EDMs can provide us with information of physics at the seesaw scale. The lepton EDMs in the framework of the SUSY type I seesaw models have been studied by many authors [7, 8, 9]. In particular, Farzan [8] studied effects of the bilinear soft SUSY breaking terms (B terms) of heavy right-handed sneutrinos. It was shown that CP violating imaginary part of the B term contributes to trilinear coupling (A term) of slepton and Higgs fields through the threshold correction at the seesaw scale, and eventually generates lepton EDMs. A similar effect in the SUSY type II seesaw model was studied by Chun, Masiero, Rossi and Vempati [10], where the B term of heavy $SU(2)_W$ triplet fields contributes to the slepton A term in the same way as in the type I case. However, the B term affects not only the slepton A term but also the $SU(2)_W \times U(1)_Y$ gaugino masses in the context of the type II seesaw model [11].

In this Letter, we study the effects of the triplet B term on lepton EDMs in the SUSY type II seesaw model taking account of the contribution from

the gaugino masses as well as that from the slepton A term. We show that the former is more important than the latter. As a result, the ratio of muon EDM to electron EDM is given by $d_\mu/d_e \simeq m_\mu/m_e$ in a wide region of parameter space. In Ref. [10], where only the effect from the slepton A term is considered, it is argued that the lepton EDM ratios are determined by the neutrino parameters. Our result is different from that of Ref. [10] because the contribution from the gaugino masses turns out to be generally larger than that from the slepton A term.

First, we briefly review the SUSY type II seesaw model. We follow the conventions of the SUSY Les Houches Accord [12] for the MSSM sector. The superpotential of the model is given by

$$\begin{aligned}
W = & \epsilon_{ab} \left(Y_E^{ij} H_1^a L_i^b \bar{E}_j + Y_D^{ij} H_1^a Q_i^b \bar{D}_j - Y_U^{ij} H_2^a Q_i^b \bar{U}_j - \mu H_1^a H_2^b \right. \\
& + \frac{1}{\sqrt{2}} Y_T^{ij} L_i^a T_1^{bc} L_j^c + \frac{1}{\sqrt{2}} \lambda_1 H_1^a T_1^{bc} H_1^c + \frac{1}{\sqrt{2}} \lambda_2 H_2^a T_2^{bc} H_2^c \Big) \\
& + M_T \text{tr}(T_1 T_2),
\end{aligned} \tag{1}$$

where Q_i^a , L_i^a , \bar{E}_i , \bar{D}_i , \bar{U}_i , H_1^a and H_2^a denote chiral supermultiplets in the MSSM with the suffixes $a, b, c = 1, 2$ and $i, j = 1, 2, 3$ being $SU(2)_W$ and generation indices, respectively. T_1 and T_2 are $SU(2)_W$ triplets with hypercharge 1 and -1 , respectively. By rephasing and rotating the fields, we can take the basis that Y_E is real and diagonal, λ_2 and M_T are real, λ_1 is complex and Y_T is a complex symmetric matrix. The relevant soft SUSY breaking terms are given by

$$\begin{aligned}
\mathcal{L}^{\text{soft}} = & -\epsilon_{ab} \left(A_E^{ij} H_1^a \tilde{L}_i^b \tilde{e}_{Rj}^* + A_D^{ij} H_1^a \tilde{Q}_i^b \tilde{d}_{Rj}^* - A_U^{ij} H_2^a \tilde{Q}_i^b \tilde{u}_{Rj}^* - B_H \mu H_1^a H_2^b \right. \\
& + \frac{1}{\sqrt{2}} A_T^{ij} \tilde{L}_i^a T_1^{bc} \tilde{L}_j^c + \frac{1}{\sqrt{2}} A_1 H_1^a T_1^{bc} H_1^c + \frac{1}{\sqrt{2}} A_2 H_2^a T_2^{bc} H_2^c + \text{h.c.} \Big) \\
& - \left(M_T B_T \text{tr}[T_1 T_2] + \text{h.c.} \right) + \frac{1}{2} \left(M_1 \tilde{b} \tilde{b} + M_2 \tilde{w} \tilde{w} + \text{h.c.} \right) \\
& - (m_L^2)_{ij} \tilde{L}_{ia}^* \tilde{L}_j^a + \dots
\end{aligned} \tag{2}$$

Here, $H_{1,2}^a$ and $T_{1,2}^{bc}$ denote scalar components of the chiral multiplets which are given by the same notations in (1). \tilde{Q}_i^a , \tilde{L}_i^a , \tilde{e}_{Ri}^* , \tilde{d}_{Ri}^* and \tilde{u}_{Ri}^* are scalar components of Q_i^a , L_i^a , \bar{E}_i , \bar{D}_i and \bar{U}_i , respectively. \tilde{b} and \tilde{w} are $U(1)_Y$ and $SU(2)_W$ gaugino fields, respectively. To avoid large flavor changing neutral

current effects, we assume that the soft SUSY breaking mass terms are universal at a high energy scale $M_G = 2 \times 10^{16}$ GeV and that the A terms are proportional to the corresponding Yukawa couplings ($A_E^{ij} = a_0 Y_E^{ij}$ etc.) at M_G . In the following, we denote the universal scalar mass by m_0 and the constant proportionality by a_0 . We also assume that gaugino masses are universal at M_G and are given by $m_{1/2}$.¹

Under these boundary conditions, there remain three CP violating phases that contribute to the EDMs: phases of μ , a_0 and B_T . The phases of $m_{1/2}$ and $B_H\mu$ are rotated away without loss of generality. Different CP violating sources contribute to lepton EDMs in different ways. Effects of the phases of μ and a_0 have been studied in detail in the literature [14]. Here we study the effect of B_T as a new source of CP violation and assume μ and a_0 to be real parameters.

The tiny neutrino masses are generated through the exchange of the triplet fields, which is given by

$$(m_\nu)_{ij} = \frac{\lambda_2}{M_T} \left(\frac{v_2}{\sqrt{2}} \right)^2 (Y_T)_{ij}. \quad (3)$$

v_2 is the vacuum expectation value of H_2 field. The matrix m_ν can be diagonalized by the Maki-Nakagawa-Sakata (MNS) matrix [15]:

$$\text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) = m_\nu^{\text{diag}} = U_{\text{MNS}}^T m_\nu U_{\text{MNS}}, \quad (4)$$

where the matrix U_{MNS} is defined as

$$U_{\text{MNS}} = V \text{diag}(e^{-i\frac{\phi}{2}}, e^{-i\frac{\phi'}{2}}, 1), \quad (5)$$

where ϕ and ϕ' are CP violating Majorana phases and V is given by

$$V = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}. \quad (6)$$

We have abbreviated $\sin \theta_{ij}$ and $\cos \theta_{ij}$ as s_{ij} and c_{ij} , respectively. Hereafter

¹ Strictly speaking, M_G is not the ‘‘GUT scale’’ since the existences of the T_1 and T_2 spoil the gauge coupling unification. We take these boundary conditions for technical simplicity. A model with grand unification constructed by embedding $T_{1,2}$ into $SU(5)$ multiplets is considered in Refs. [13, 11].

we use the following parameters:

$$\begin{aligned}\Delta m_{21}^2 &= m_{\nu_2}^2 - m_{\nu_1}^2 = 8.0 \times 10^{-5} \text{ eV}^2, \\ |\Delta m_{32}^2| &= |m_{\nu_3}^2 - m_{\nu_2}^2| = 2.5 \times 10^{-3} \text{ eV}^2, \\ \sin \theta_{12} &= 0.56, \quad \sin \theta_{23} = 0.71, \quad \sin \theta_{13} = 0.01,\end{aligned}\tag{7}$$

and assume that $m_{\nu_1} \sim 0 \text{ eV}$ which corresponds to the normal hierarchy of the neutrino masses. We take the values of Δm_{21}^2 , $|\Delta m_{32}^2|$, $\sin \theta_{12}$ and $\sin \theta_{23}$ from Ref. [16]. Note here that $Y_T^\dagger Y_T$ can be written as follows,

$$(Y_T^\dagger Y_T)_{ij} \simeq \left(\frac{0.01}{\lambda_2} \right)^2 \left(\frac{1 + \tan^2 \beta}{\tan^2 \beta} \right)^2 \left(\frac{|M_T|}{10^{13} \text{ GeV}} \right)^2 \left(\frac{\sum_k m_{\nu k}^2 U_{\text{MNS}}^{ik} U_{\text{MNS}}^{jk*}}{10^{-3} \text{ eV}^2} \right),\tag{8}$$

where we have substituted 246 GeV into the vacuum expectation value $v = \sqrt{v_1^2 + v_2^2}$ and the $\tan \beta$ is defined by the ratio of the vacuum expectation values of the two Higgs fields: $\tan \beta = v_2/v_1$. In the type II seesaw model, the Yukawa coupling Y_T is directly related to the neutrino masses and the MNS matrix in contrast to the type I seesaw model.

We calculate lepton EDMs in the SUSY type II seesaw model with use of the following procedure. We solve the renormalization group equations for the parameters in the SUSY type II seesaw model from M_G scale to M_T with the input parameters m_0 , a_0 and $m_{1/2}$ at M_G .² Next, at M_T scale, we calculate one-loop threshold corrections for the matching of the parameters in the SUSY type II seesaw model and those in the MSSM as an effective theory in the low energy scale. Then the renormalization group equations for the MSSM parameters are solved down to the electroweak scale to evaluate masses and mixing matrices of the SUSY particles. Finally we calculate the lepton EDMs with chargino-sneutrino and neutralino-charged slepton one-loop diagrams.

The B_T term contributes to the threshold corrections only at the M_T scale where the triplet fields $T_{1,2}$ are integrated out. There are two main contributions from B_T : threshold corrections to the A terms and those to the gaugino masses. The threshold correction to the slepton A term, denoted by δA_E , is generated through the diagrams shown in Fig. 1. Keeping auxiliary

²The renormalization group equations that we have used agree with the relevant part of those given in Ref. [17].

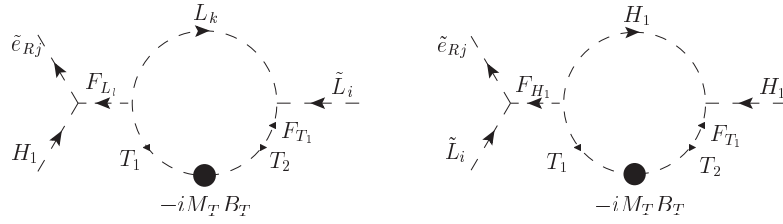


Figure 1: One-loop Feynman diagrams that contribute to δA_E . Fields F_{T_1, H_1, L_i} represent auxiliary fields of supermultiplets.

fields as independent fields [9], we can easily calculate the correction δA_E :

$$\delta A_E = \frac{3}{16\pi^2} B_T (Y_T Y_T^\dagger + |\lambda_1|^2) Y_E. \quad (9)$$

Since T_1 and T_2 fields have $SU(2)_W \times U(1)_Y$ gauge charges, threshold corrections to the electroweak gaugino masses $M_{1,2}$ are generated. One-loop correction terms proportional to B_T are induced by the diagram shown in Fig. 2. We obtain the threshold corrections δM_1 and δM_2 as

$$\delta M_1 = -\frac{6}{16\pi^2} g^2 B_T, \quad (10)$$

$$\delta M_2 = -\frac{4}{16\pi^2} g^2 B_T. \quad (11)$$

CP violating imaginary part of B_T contributes to the lepton EDMs through these threshold corrections.

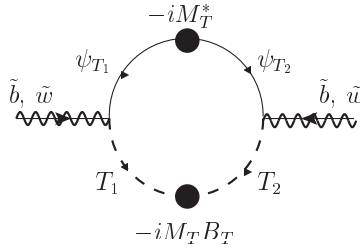


Figure 2: One-loop Feynman diagram which gives threshold corrections to the gaugino masses.

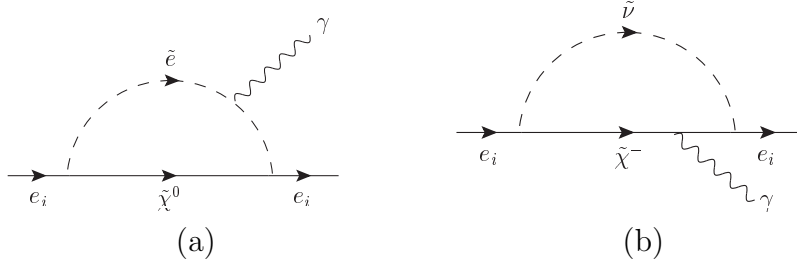


Figure 3: One-loop diagrams contributing to lepton EDMs.

Let us examine the effects from δA_E and $\delta M_{1,2}$ on the lepton EDMs. Lepton EDMs are induced by the one-loop diagrams shown in Fig. 3. Contributions of B_T through the neutralino-charged slepton diagram (Fig. 3(a)) are schematically given by

$$d_i^{\text{Im}A_E} \sim \frac{eg'^2}{(16\pi^2)^2} \frac{m_{e_i}}{m_{\text{SUSY}}^4} \text{Re}M_1 [(Y_T Y_T^\dagger)_{ii} + |\lambda_1|^2] \text{Im}B_T, \quad (12)$$

$$d_i^{\text{Im}M_1} \sim \frac{eg'^2}{(16\pi^2)^2} \frac{m_{e_i}}{m_{\text{SUSY}}^4} (\mu g'^2 \tan \beta) \text{Im}B_T, \quad (13)$$

where $d_i^{\text{Im}A_E}$ and $d_i^{\text{Im}M_1}$ are contributions of δA_E and δM_1 , respectively. m_{SUSY} means a typical scale of SUSY particle masses in the loop. Contribution of B_T in the chargino-sneutrino diagram (Fig. 3(b)) through δM_2 is given by

$$d_i^{\text{Im}M_2} \sim \frac{eg^2}{(16\pi^2)^2} \frac{m_{e_i}}{m_{\text{SUSY}}^4} (\mu g^2 \tan \beta) \text{Im}B_T. \quad (14)$$

We can see that the flavor dependence of the lepton EDMs induced by (13), (14) and the term proportional to $|\lambda_1|^2$ in (12) comes only from the lepton mass in the overall factor. On the other hand, the term proportional to $(Y_T Y_T^\dagger)_{ii}$ in (12) has extra lepton flavor dependence determined by the neutrino masses and mixings. Therefore, if the contribution from $(Y_T Y_T^\dagger)_{ii}$ dominates, the ratios of the lepton EDMs differ significantly from the corresponding lepton mass ratios. Otherwise, the lepton EDM ratios are approximately equal to the lepton mass ratios. In Ref. [10], it is argued that the ratios of EDMs are given by

$$\frac{d_i}{d_j} \simeq \frac{m_{e_i}}{m_{e_j}} \frac{(Y_T Y_T^\dagger)_{ii}}{(Y_T Y_T^\dagger)_{jj}}, \quad (15)$$

taking the contribution from Eq. (12) into account with the assumption $|\lambda_1|^2 \ll Y_T Y_T^\dagger$. If this relation is valid, we obtain $d_\mu/d_e \sim 10^4$ and $d_\tau/d_\mu \sim 17$ substituting the neutrino parameters shown in Eq. (7) for the normal hierarchy of neutrino masses. However, since the contributions from Eq. (13) and Eq. (14) are missing in Ref. [10], we calculate lepton EDMs including all the contributions in the following.

In this model, it is known that the branching ratios of the lepton flavor violating (LFV) processes such as $l_i \rightarrow l_j \gamma$ decays can be large because of new source of lepton flavor mixing Y_T [13]. Therefore, we calculate the branching ratios of $l_i \rightarrow l_j \gamma$ as well as the lepton EDMs. Since the $l_i \rightarrow l_j \gamma$ processes are induced by one-loop diagrams of charginos (neutralinos) and sleptons, the branching ratios $\text{Br}(l_i \rightarrow l_j \gamma)$ are proportional to $|(m_L^2)_{ij}|^2$. In the SUSY type II seesaw model, the off-diagonal elements of m_L^2 are mainly generated by the running between the M_G and M_T scales, which are roughly estimated as

$$(m_L^2)_{ij} \sim -\frac{m_0^2}{16\pi^2} (Y_T^\dagger Y_T)_{ij} \ln \frac{M_G^2}{M_T^2}. \quad (16)$$

In the numerical calculations, this effect is implicitly included in the process of solving renormalization group equations. We also take account of threshold corrections at M_T , which turn out to be smaller than Eq. (16) by a factor of $\ln(M_G/M_T)$.

We show our numerical results of the branching ratio of $\mu \rightarrow e \gamma$, the EDMs of electron (d_e), muon (d_μ) and tau (d_τ), and the ratio of d_μ and d_e as functions of λ_2 evaluated at M_T scale for three cases of $M_T = 10^{12}$, 10^{13} and 10^{14} GeV in Fig. 4. We fix other input parameters as $\lambda_1 = 0$, $\tan \beta = 3$, $m_0 = m_{1/2} = 300$ GeV, $a_0 = 0$ GeV and $\text{Re} B_T = \text{Im} B_T = 100$ GeV. We take the Higgsino mass parameter μ as $\mu > 0$. In Figs. 4(a) and 4(b), current upper bounds of the branching ratio of $\mu \rightarrow e \gamma$ $\text{Br}(\mu \rightarrow e \gamma) < 1.2 \times 10^{-11}$ [18] and the electron EDM $|d_e| < 1.6 \times 10^{-27} e \text{ cm}$ [1] are shown, respectively. Since Y_T is determined from M_T , λ_2 and the neutrino parameters (7) by Eq. (3), a large (small) λ_2 corresponds to small (large) Y_T for a fixed M_T . The lower limit of λ_2 in each plot is determined by the conditions that Y_T remains finite up to M_G and the slepton masses squared are positive at the electroweak scale. The upper limit of λ_2 is set by the condition that λ_2 does not blow-up below M_G . We can see that the ratio d_μ/d_e is around 200 except for the lower end of λ_2 in each curve, but never becomes 10^4 as predicted in Eq. (15). The reason why d_μ and d_μ/d_e grow at the smallest values of λ_2 is that the mass of the lightest slepton which couples to muon rather

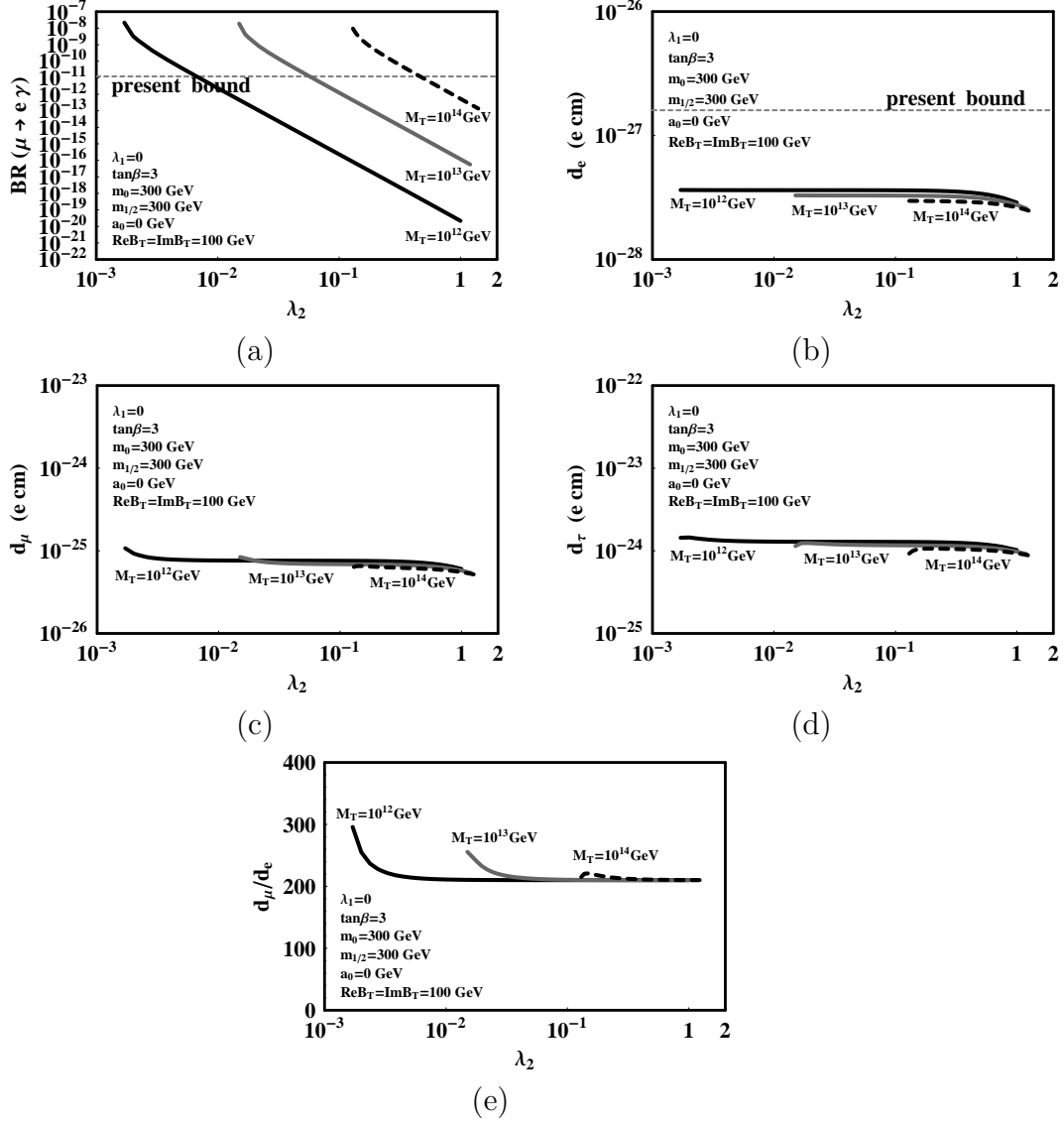


Figure 4: (a) The branching ratio of $\mu \rightarrow e \gamma$, (b) the electron EDM, (c) the muon EDM, (d) the tau EDM and (e) the ratio of the muon EDM to the electron EDM as functions of λ_2 for $\lambda_1 = 0$, $\tan\beta = 3$, $m_0 = m_{1/2} = 300$ GeV, $a_0 = 0$ GeV and $\text{Re}B_T = \text{Im}B_T = 100$ GeV. Black and gray solid lines and dashed lines are for $M_T = 10^{12}$, 10^{13} and 10^{14} GeV, respectively. The input value of $\lambda_{1,2}$ and B_T are given at the scale M_T while those of m_0 , $m_{1/2}$ and a_0 are given at the scale M_G .

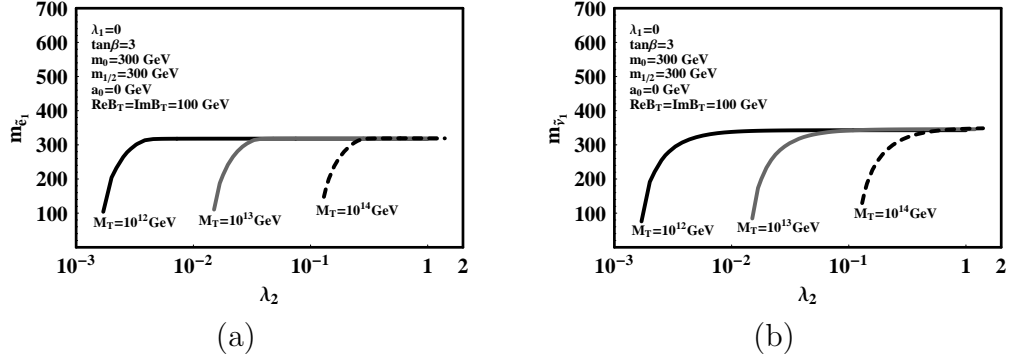


Figure 5: Masses of the lightest charged slepton and the lightest sneutrino as functions of λ_2 . Input parameters are the same as those in Fig. 4.

than electron rapidly decreases due to the large Y_T as shown in Fig. 5. This result implies that the contributions from $\delta M_{1,2}$ are much larger than that from δA_E in the whole parameter region³. As seen in Fig. 4(a), $\text{Br}(\mu \rightarrow e\gamma)$ exceeds the current experimental upper limit in the region where d_μ/d_e deviates from the lepton mass ratio m_μ/m_e . This is because $\text{Br}(\mu \rightarrow e\gamma)$ is enhanced by the large splitting among the slepton masses due to the large Y_T . Consequently, after the experimental constraint on $\text{Br}(\mu \rightarrow e\gamma)$ is imposed, $d_\mu/d_e \simeq m_\mu/m_e$ is satisfied in allowed parameter region. As for d_τ , we obtain $d_\tau/d_\mu \simeq m_\tau/m_\mu \simeq 17$ in the whole parameter region. We also calculate the branching ratios of $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$. We confirm that $\text{Br}(l_i \rightarrow l_j\gamma)$ are controlled by the neutrino parameters as discussed in Refs. [13, 10, 11], since the LFVs are determined by Y_T in this model.

In Fig. 6, we show the branching ratio of the $\mu \rightarrow e\gamma$ decay, d_e , d_μ , d_τ and d_μ/d_e as functions of the lightest charged slepton mass $m_{\tilde{e}_1}$. We vary m_0 within $100 \text{ GeV} \leq m_0 \leq 1000 \text{ GeV}$ and fix other parameters as $\lambda_1 = 0$, $\lambda_2 = 0.03$, $M_T = 10^{12} \text{ GeV}$, $a_0 = 0 \text{ GeV}$, $\text{Re} B_T = \text{Im} B_T = 100 \text{ GeV}$. For $\tan\beta$ and $m_{1/2}$, we take the cases with $\tan\beta = 3, 30$ and $m_{1/2} = 300, 600 \text{ GeV}$. We see that the relation $d_\mu/d_e \simeq m_\mu/m_e$ holds in all cases.⁴

³ We confirmed that the same results are obtained in the case we drop the contribution from δA_E by hand. In the case we drop the contribution from $\delta M_{1,2}$ by hand, we can reproduce the results of the Ref. [10].

⁴ We have also calculated SUSY contribution to the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$. Within the parameter space we have searched for, we obtain $0 \lesssim a_\mu(\text{SUSY}) \lesssim 40 \times 10^{-10}$ in the case of $\mu > 0$. This result is consistent with current experimental value [20].

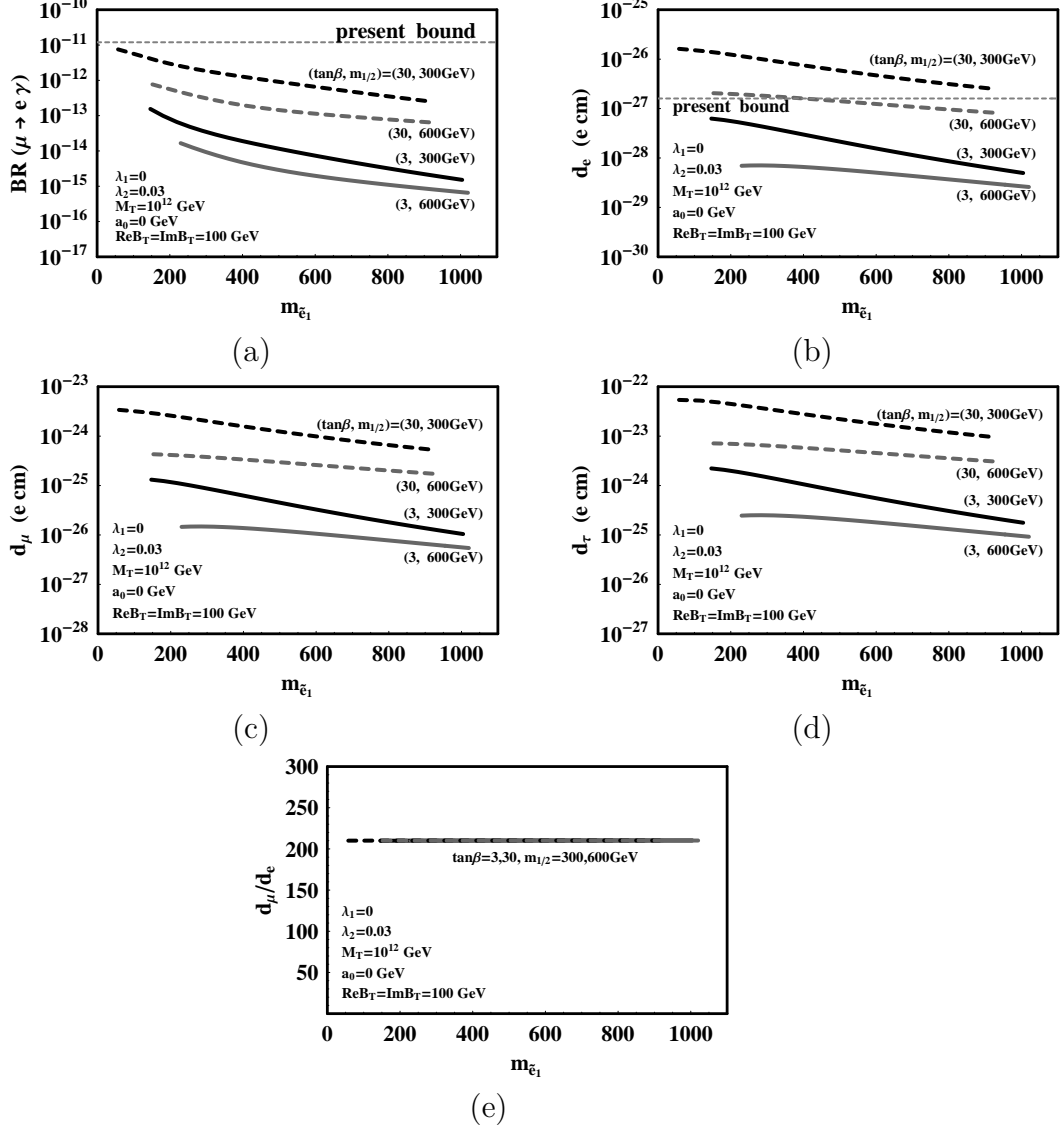


Figure 6: (a) The branching ratio of $\mu \rightarrow e \gamma$, (b) the electron EDM, (c) the muon EDM, (d) the tau EDM and (e) the ratio of the muon EDM to the electron EDM as functions of the lightest charged slepton mass $m_{\tilde{e}_1}$ for $\lambda_1 = 0$, $\lambda_2 = 0.03$, $M_T = 10^{12} \text{ GeV}$, $a_0 = 0 \text{ GeV}$ and $\text{Re} B_T = \text{Im} B_T = 100 \text{ GeV}$. Black and gray solid lines are for $(\tan \beta, m_{1/2}) = (3, 300 \text{ GeV})$ and $(3, 600 \text{ GeV})$, respectively, while black and gray dashed lines are for $(\tan \beta, m_{1/2}) = (30, 300 \text{ GeV})$ and $(30, 600 \text{ GeV})$, respectively.

In this Letter, we have studied leptonic EDMs in the SUSY type II seesaw model including all contributions generated by one-loop threshold corrections to SUSY breaking parameters at the seesaw scale through the bilinear soft SUSY breaking term of the $SU(2)_W$ triplet fields. We have shown that the ratios of the leptonic EDMs are given by those of the lepton masses in a good approximation for most of parameter space. We have presented numerical results for some specific cases, but this conclusion holds unless fine tuning of parameters is made. For instance, we have checked that the same conclusion is valid for the case of $\lambda_1 \neq 0$ or other types of neutrino mass hierarchy. We have also relaxed the relation $M_1 = M_2$ at the GUT scale and found that the ratios of the EDMs do not change even if we varied M_1/M_2 within the range $1/10 \leq M_1/M_2 \leq 10$. This result suggests that muon EDM is predicted to be 200 times larger than the electron EDM in the SUSY type II seesaw model, which is contrasted with the type I model where the relation is more complicated because the B term phase contributions to the EDMs depend on neutrino Yukawa couplings [8]. Since the upper bound of the electron EDM is at the level of $10^{-27} e \text{ cm}$, planned dedicated experiments [19] of the muon EDM search at the level of $10^{-24} - 10^{-25}$ are very important.

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